

Instructor's Manual

Mechatronics

Electronic Control Systems in Mechanical and Electrical Engineering

Seventh edition

William Bolton

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Instructor's Guide

This manual includes:

1. Supporting notes for lecturers
2. Multiple-choice tests
3. Supporting material: Electrical components and circuits

Supporting notes for lecturers

About this resource manual

This resource manual is designed to support the seventh edition of the book *Mechatronics* by indicating how the book might be used and providing multiple-choice tests.

About the book

The first edition was designed to cover the Business and Technology Education Council (BTEC) Mechatronics units for Higher National Certificate/Diploma courses for technicians and designed to fit alongside more specialist units such as those for design, manufacture and maintenance determined by the application area of the course. The book was widely used for such courses and has also found use in undergraduate courses in both Britain and in the United States. Following feedback from lecturers in both Britain and the United States, the second edition was considerably extended and with its extra depth it was not only still relevant for its original readership but also suitable for undergraduate courses. The third edition involved refinements of some explanations, more discussion of microcontrollers and programming, increased use of models for mechatronics systems, and the grouping together of key facts in the Appendices. The fourth edition was a complete reconsideration of all aspects of the text, both layout and content, with some regrouping of topics, movement of more material into Appendices to avoid disrupting the flow of the text, new material – in particular an introduction to artificial intelligence, more case studies and a refinement of some topics to improve clarity. Also, objectives and key point summaries were included with each chapter. The fifth edition kept the same structure but, after consultation with many users of the book, many aspects have had extra detail and refinement added.

The sixth edition involved a restructuring of the constituent parts of the book as some users felt that the chapter sequencing did not match the general teaching sequence. Other changes included the inclusion of material on Arduino and the addition of more topics in the Mechatronics Systems chapter. The seventh edition has continued the evolution of the book with updating of mechatronics system components, clarification of some aspects so they read more easily, the inclusion of information on the Atmega microcontrollers, a discussion and examples of fuzzy logic and neural control systems and yet more applications and case studies. The number of Appendices has been reduced as they had grown over previous editions and it was felt that some were now little used. Appendix G Electrical circuit analysis has, with some extension, been moved to this Instructor's guide.

The overall aim of the book is to give a comprehensive coverage of mechatronics which can be used with courses for both technicians and undergraduates in engineering, and hence, to help the reader:

1. Acquire a mix of skills in mechanical engineering, electronics and computing which is necessary if he/she is to be able to comprehend and design mechatronics systems.
2. Become capable of operating and communicating across the range of engineering disciplines necessary in mechatronics.
3. Be capable of designing mechatronic systems.

Each chapter of the book includes objectives, a summary, is copiously illustrated and contains problems, answers to which are supplied at the end of the book. With Chapter 24 research and design assignments are also included, clues as to their possible answers also being given.

Order of work in the text

The book has been written so that a comprehensive coverage of mechatronics is given by starting at Chapter 1 and working steadily through the chapters in the sequence given. The course structure is then the topics of:

Part I Introduction

Chapter 1 is a general introduction to mechatronics.

Part II Sensors and signal conditioning

Chapters 2 to 6 form a coherent block on sensors and signal conditioning.

Part III Actuation

Chapters 7 to 9 cover actuators.

Part IV Microprocessor systems

Chapters 10 to 16 are concerned with microprocessor systems.

Part V System models

Chapters 17 to 23 are concerned with system models.

Part VI Conclusion

Chapter 24 provides an overall conclusion in considering the design of mechatronics systems.

The objectives of individual chapters

Chapter 1 Introducing Mechatronics

Explain what is meant by mechatronics and appreciate its relevance in engineering design.

Explain what is meant by a system and define the elements of measurement systems.

Describe the various forms and elements of open-loop and closed-loop systems.

Recognise the need for models of systems in order to predict their behaviour.

This chapter is a general introduction to the subject of mechatronics, touching on all the main aspects involved in the design of such systems, these all being considered in more detail in the rest of the book.

Chapter 2 Sensors and transducers

Describe the performance of commonly used sensors using terms such as range, span, error, accuracy, sensitivity, hysteresis and non-linearity error, repeatability, stability, dead band, resolution, output impedance, response time, time constant, rise time and settling time.

Evaluate sensors used in the measurement of displacement, position and proximity, velocity and motion, force, fluid pressure, liquid flow, liquid level, temperature and light intensity.

Explain the problem of bouncing when mechanical switches are used for inputting data and how it might be overcome.

This considers the terminology used to describe the performance of sensors and transducers and then discusses the principles of commonly encountered sensors.

Chapter 3 Signal conditioning

Explain the requirements for signal conditioning.

Explain how operational amplifiers can be used.

Explain the requirements for protection and filtering.

Explain the principles of the Wheatstone bridge and, in particular, how it is used with strain gauges.

Explain the principle of pulse modulation.

Explain the problems that can occur with ground loops and interference and suggest possible solutions to these problems.

State the requirements for maximum power transfer between electrical components.

This chapter is a consideration of the main methods used in signal conditioning. In particular there is a long section on the operational amplifier, this being drawn on considerably in later chapters.

Chapter 4 Digital signals

Explain the principles and main methods of analogue-to-digital and digital-to-analogue converters.

Explain the principles and uses of multiplexers.

Explain the principles of digital signal processing.

This follows on from the previous chapter. An elementary introduction to digital signal processing is included.

Chapter 5 Digital logic

Recognise the symbols for logic gates AND, OR, NOT, NAND, NOR and XOR, and use such gates in applications., recognising the significance of logic families.

Explain how SR, JK and D flip-flops can be used in control systems.

Explain the operation of decoders and the 555 timer.

This chapter is a basic introduction to combinational and sequential digital logic. Appendix B: Number Systems and Appendix C: Boolean algebra might be used in conjunction with this chapter.

Chapter 6 Data presentation elements

Explain the problem of loading in measurement systems.

Identify commonly used data presentation elements and describe their characteristics.

Explain the principles of magnetic and optical recording.

Explain the principles of displays, in particular the LED seven-segment and dot matrix displays.

Describe the basic elements of data acquisition systems and data loggers.

This chapter is a basic introduction to the output presentation of data.

Chapter 7 Pneumatic and hydraulic actuation systems

Interpret system drawings and design simple systems, for sequential control systems involving hydraulic/pneumatic directional control valves and cylinders.

Explain the principles of process control valves, their characteristics and sizing.

This chapter has essentially two main parts: a consideration of the use of directional control valves in the design of sequential control systems and the use of process control valves in closed-loop process control systems. The sequential control systems are picked up and further discussed in later chapters.

Chapter 8 Mechanical actuating systems

Determine possible mechanical actuation systems for motion transmission involving liner-to-rotary, rotary-to-rotary, rotary-to-linear and cyclic motion transmission.

Evaluate the capabilities of linkages, cams, gears, ratchet-and-pawl, belt and chain drives and bearings for actuation systems.

This is a general overview of the main mechanical actuation elements. Linkage mechanisms and cams features in design solutions in the final chapter of the text.

Chapter 9 Electrical actuation systems

Evaluate the operational characteristics of electrical actuation systems: relays, solid-state switches (thyristors, bipolar transistors and MOSFETs), solenoids, d.c. motors, a.c. motors, steppers and d.c. servo motors.

Explain the principles of d.c. motors, including the d.c. permanent magnet motor and how it can have speed control.

Explain the principles of the brushless permanent magnet d.c. motor.

Explain the principles of the variable reluctance, permanent magnet, hybrid forms of stepper motor and how step sequences can be generated, and the d.c. servo motor.

Explain the requirements in selecting motors of inertia matching and torque and power requirements.

This is a key chapter in the discussion of actuators for use with microprocessor control systems, in particular the control of motors, and is drawn on in many of the later chapters.

Chapter 10 Microprocessors and Microcontrollers

Describe the basic structure of a microprocessor system.

Describe the architecture of common microprocessors and how they can be incorporated in microprocessor systems.

Describe the basic structure of microcontrollers and how their registers can be set to carry out tasks.

Explain how programs can be developed using flow charts and pseudocode.

This chapter is a basic introduction to the structure of microprocessor and microcontroller systems with examples of commonly encountered systems.

Chapter 11 Assembly language

Use assembly language to write programs involving data transfers, arithmetic, logic, jumps, branches, subroutines, delays and look-up tables.

Where lecturers mainly use C, this chapter might just be given a cursory consideration.

Chapter 12 C language

Comprehend the main features of C programs.

Use C to write simple programs for microcontrollers.

Write programs for Arduino boards.

This is a basic general introduction to the use of C to write programs for microprocessor-based systems.

Chapter 13 Input/output systems

Identify interface requirements and how they can be realised: buffers, handshaking, polling and serial interfacing.

Explain how interrupts are used with microcontrollers.

Explain the functions of peripheral interface adapters and be able to program them for particular situations.

Explain the function of asynchronous communication interface adapters.

This is a key chapter in the development of applications for microprocessor-based systems.

Chapter 14 Programmable logic controllers

Describe the basic structure of PLCs and their operation.

Develop ladder programs for a PLC involving logic functions, latching, internal relays and sequencing.

Develop programs involving timers, counters, shift registers, master relays, jumps and data handling.

This is a basic introduction to the use of PLCs and the writing of ladder programs. Where PLCs are available, it can be usefully used to develop many assignments with students who otherwise struggle with writing programs.

Chapter 15 Communication systems

Describe centralised, hierarchical and distributed control systems, network configurations and methods of transmitting data and protocols used.

Describe the Open Systems Interconnection communication modes.

Describe commonly used communication interfaces: RS-232, IEEE 488, 20 mA current loop, I²C bus and CAN.

This chapter is a discussion of methods used for the linking together of microprocessor-based systems, computers and instruments.

Chapter 16 Fault finding

Recognise the techniques used to identify faults in microprocessor-based systems, including both hardware and software.

Explain the use of emulation and simulation.

Explain how fault finding can be achieved with PLC systems.

This is a general discussion of fault finding for systems that might have been developed from consideration of the earlier sections of this book and also arise in the following chapters.

Chapter 17 Basic system models

Explain the importance of models in predicting the behaviour of systems.

Devise models from basic building blocks for mechanical, electrical, fluid and thermal systems.

Recognise analogies between mechanical, electrical, fluid and thermal systems.

This chapter is the introduction to the group of chapters on system models and leads in later chapters to indicating how differential equations can be developed for systems so that their performance with time can be determined when they are subject to inputs.

Chapter 18 System models

Devise models for rotational-translational, electromechanical and hydraulic-mechanical systems.

Linearize non-linear relationships in order to generate linear models.

This extends chapter 10 to more complex systems.

Chapter 19 Dynamic responses of systems

Model dynamic systems by means of differential equations.

Determine the outputs of first-order systems to inputs and determine time constants.

Determine the outputs of second-order systems to inputs and identify the under-damped, critically damped and over-damped conditions.

Describe the characteristics of second-order system responses in terms of rise time, overshoot, subsidence ration, decrement and settling time.

This looks at the solution of the differential equations that have been devised for models and thus how such systems will react when subject to various inputs.

Chapter 20 System transfer functions

Define the transfer function and determine it from differential equations for first- and second-order systems.

Determine the transfer function for systems with feedback loops.

Determine, using Laplace transforms, the responses of first- and second-order systems to simple inputs.

Determine the effect of pole location on the responses of systems.

This introduces the transfer function and the Laplace transform, Appendix A giving a more detailed consideration.

Chapter 21 Frequency response

Explain the meaning of the frequency-response function.

Analyse the frequency response of systems subject to sinusoidal inputs.

Plot and interpret Bode plots.

Use Bode plots for system identification.

Explain the term bandwidth.

Explain how the gain margin and phase margin can be used to indicate the stability of a system.

Following an initial discussion of phasors, this chapter considers the frequency response of systems.

Chapter 22 Closed-loop controllers

Explain the term steady-state error.

Explain the operation of the two-step mode of control.

Explain the behaviour of systems with proportional, integral, derivative, proportional plus integral, proportional plus derivative and PID control.

Describe how digital controllers operate.

Explain how controllers can be tuned.

This is a key chapter in any discussion of closed-loop control. While the chapter has been written as following the discussion of system models, it would be possible to use this chapter without such a background.

Chapter 23 Artificial intelligence

Explain what is meant by an intelligent machine and the capabilities of such machines.

Explain the meaning of artificial neural networks and their relevance to pattern recognition.

Explain the term fuzzy logic and its applications in modern machines.

This chapter is a basic introduction to the subject of artificial intelligence.

Chapter 24 Mechatronic systems

Develop possibly solutions to design problems when considered from the mechatronics point of view.

Describe the basic elements used in robotics.

Analyse case studies of mechatronic solutions.

This chapter is designed to draw together many of the principles discussed in earlier chapters and lead to a consideration of mechatronic case studies and design assignments for students.

Multiple-choice tests

The following are multiple-choice tests, answers being given at the end of the tests. For the tests, the chapters have been grouped to enable lecturers to be able to use the tests if different routes are taken or blocks omitted. The tests are:

1. Sensors and signal conditioning

On Chapters 2, 3, 4 and 6

2. Actuation

On Chapters 7, 8 and 9

3. System models

On Chapters 17, 18, 19, 20, 21 and 22

4. Microprocessor systems

On Chapters 10, 11, 12, 13, 14, 15 and 16

TEST 1

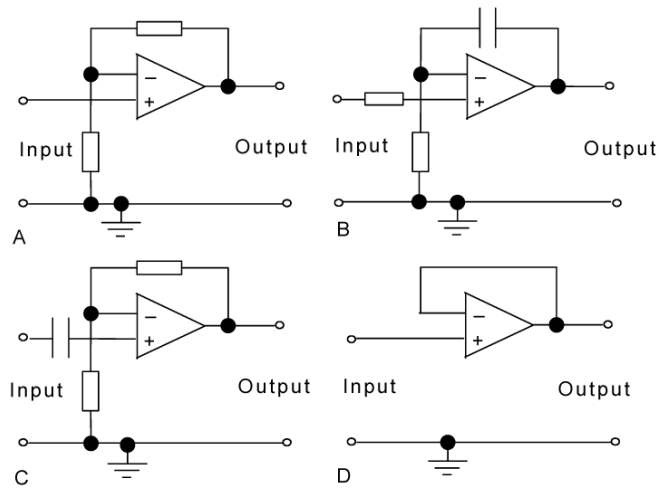
Sensors and signal conditioning

For the following questions, you have four answer options A, B, C and D. Choose the correct answer from the answer options.

1. A pressure sensor has a range of 0 to 1,000 kPa and a non-linearity error of $\pm 0.15\%$ of full range and a hysteresis error of $\pm 0.05\%$ of full range. The error for a reading of 300 kPa is:
A ± 0.3 kPa
B ± 0.6 kPa
C ± 1.0 kPa
D ± 2.0 kPa
2. A sensor, for an input of 4 V, gives a digital output of a word of 8 bits. The resolution is:
A $4/8$ V
B $8/4$ V
C $4/2^8$ V
D $2^8/4$ V
3. Decide whether each of these statements is TRUE (T) or FALSE (F).
A sensor has a thermal sensitivity of 0.030% full range output / $^{\circ}\text{C}$ and two ranges 50 to 1,000 kPa and 1,000 to 60,000 kPa. When there is a temperature change of 1°C , the sensitivity changes by:
(i) 0.3 kPa on the lower range.
(ii) 18 kPa on the upper range.
Which option BEST describes the two statements?
A (i) T (ii) T
B (i) T (ii) F
C (i) F (ii) T
D (i) F (ii) F
4. A thermocouple sensor has a time constant of 50 s in still air. When it is subject to a temperature change of 100°C , in 50 s its temperature will have changed by about:
A 31°C
B 50°C
C 63°C
D 100°C

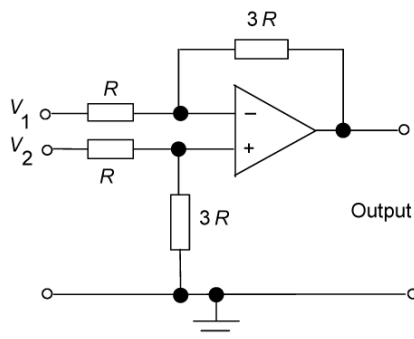
5. A linear potentiometer of resistance $1\text{ k}\Omega$ has a load of resistance $10\text{ k}\Omega$ connected across it. When the supply voltage across the potentiometer is 4 V and the potentiometer slider is at the mid-point, there will be a non-linearity error due to loading of:
- A 0.05 V
 - B 0.20 V
 - C 0.40 V
 - D 0.50 V
6. Absolute encoders are used to determine the angular position of a shaft and to avoid false counting when the shaft rotates:
- A Binary code is used.
 - B Gray code is used.
 - C BCD code is used.
 - D Hex code is used.
7. The change in resistance of an electrical resistance strain gauge with a gauge factor of 2.0 and a resistance of $100\text{ }\Omega$ when subject to a strain of 0.001 is:
- A $0.05\text{ }\Omega$
 - B $0.1\text{ }\Omega$
 - C $0.2\text{ }\Omega$
 - D $2.0\text{ }\Omega$
8. A T-thermocouple, with a cold junction temperature of 0°C , is to be used to measure temperatures between 0 and 200°C . Tables give the e.m.f. for a cold junction of 0°C as 4.277 mV at 100°C and 9.286 mV at 200°C . If a linear relationship is assumed over the full range for this sensor, the linearity error at 100°C will be:
- A -3.9°C
 - B -7.9°C
 - C $+3.9^\circ\text{C}$
 - D $+7.9^\circ\text{C}$
9. A thermocouple is used with a compensation circuit:
- A Because the e.m.f. is not a linear function of temperature.
 - B To increase the time constant of the sensor.
 - C To amplify the small thermoelectric e.m.f.
 - D Because the cold junction is not held at 0°C .

Questions 10 to 12 relate to the following information. The following are operational amplifier circuits:



Select the operational amplifier circuit that will give the following outputs:

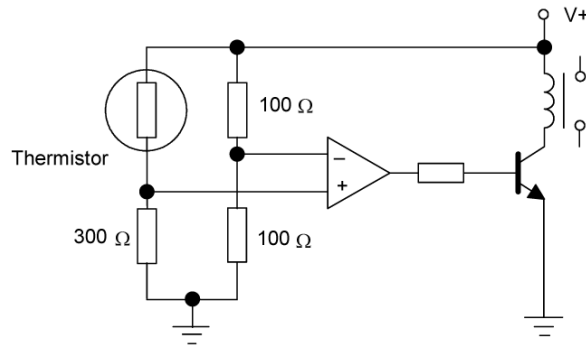
10. An output that is a linear function of the input.
11. An output that always has a voltage gain of 1.
12. An output that is proportional to the integral of the input voltage.
13. For the operational amplifier circuit shown in the following figure:



The output is:

- A Three times the sum of V_1 and V_2 .
- B Three times the difference between V_1 and V_2 .
- C Twice the sum of V_1 and V_2 .
- D Twice the difference between V_1 and V_2 .

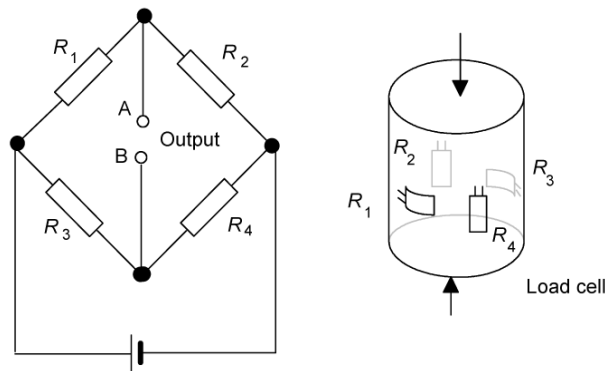
14. The operational amplifier circuit shown in the following figure includes a thermistor.



The relay must be activated when the thermistor resistance is:

- A Less than $100\ \Omega$.
 - B $200\ \Omega$.
 - C Between 100 and $300\ \Omega$.
 - D More than $300\ \Omega$.
15. Decide whether each of these statements is TRUE (T) or FALSE (F).

The Wheatstone bridge shown in the following figure is balanced when there is no load on the load cell.



When the load is applied to the load cell:

- (i) R_1 increases.
- (ii) The potential at A is greater than that at B.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

16. The resolution of an analogue-to-digital converter with a word length of 8 bits and an analogue signal input range of 10 V is:

A 39 mV
B 256 mV
C 1.25 V
D 5 V

17. Decide whether each of these statements is TRUE (T) or FALSE (F).

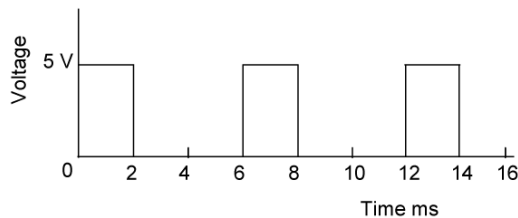
The ZN439 successive approximations 8-bit ADC has a conversion time of 5 μ s. It is thus suitable for:

- (i) Signals without aliasing with frequencies less than 100 kHz.
(ii) Giving an output for an input of 2 V with a resolution of 5 μ V.

Which option BEST describes the two statements?

A (i) T (ii) T
B (i) T (ii) F
C (i) F (ii) T
D (i) F (ii) F

18. Pulse width modulation is used to give the following signal from a 5 V DC input.



The duty cycle has the numerical value of:

A 33.3
B 83.3
C 166.7
D 500

19. Decide whether each of these statements is TRUE (T) or FALSE (F).

With the non-return-to-zero method of digital magnetic recording:

- (i) Magnetic saturation in one direction represents 0 and in the other direction 1.
(ii) A clocking signal is required.

Which option BEST describes the two statements?

A (i) T (ii) T
B (i) T (ii) F
C (i) F (ii) T
D (i) F (ii) F

20. Decide whether each of these statements is TRUE (T) or FALSE (F).

With the common anode method of connecting LED displays to a driver:

- (i) When the output goes low a display element is switched on.
- (ii) The anodes of each LED is connected directly to an input line.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

Questions 21 to 23 refer to the following four truth tables.

A	Inputs		Output
	A	B	Q
	0	0	0
	0	1	1
	1	0	1
	1	1	1

B	Inputs		Output
	A	B	Q
	0	0	0
	0	1	0
	1	0	0
	1	1	1

C	Inputs		Output
	A	B	Q
	0	0	1
	0	1	1
	1	0	1
	1	1	0

D	Inputs		Output
	A	B	Q
	0	0	0
	0	1	1
	1	0	1
	1	1	0

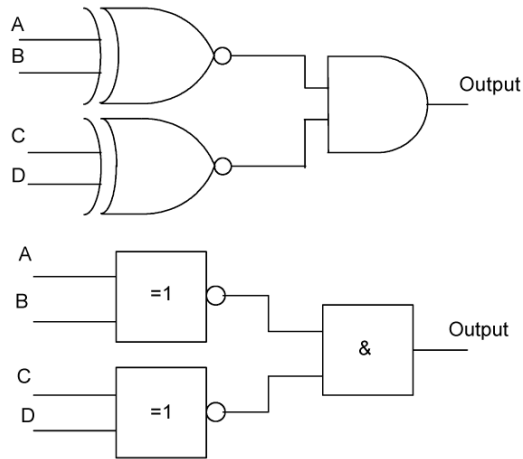
21. Which is the truth table for the AND gate?

22. Which is the truth table for the OR gate?

23. Which is the truth table for the XOR gate?

24. Decide whether each of these statements is TRUE (T) or FALSE (F).

For the logic gate circuit shown in the following figure:



When the input is:

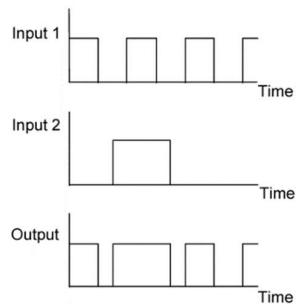
(i) $A = 0, B = 0, C = 0, D = 0$ the output is 1.

(ii) $A = 1, B = 0, C = 1, D = 0$ the output is 0.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

25. The following timing diagrams are for a two-input logic gate.

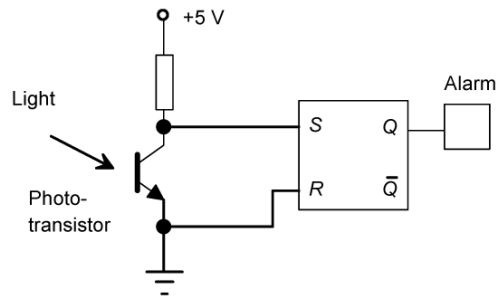


The logic gate is:

- A AND
- B OR
- C NOR
- D NAND

26. Decide whether each of these statements is TRUE (T) or FALSE (F).

For the *SR* flip-flop circuit shown in the following figure:



- (i) When the light beam is interrupted, the alarm sounds.
- (ii) After an interruption, when the light again falls on the transistor, the alarm switches off.

Which option BEST describes the two statements?

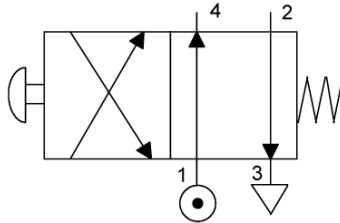
- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

TEST 2

Actuation

For the following questions, you have four answer options A, B, C and D. Choose the correct answer from the answer options.

Questions 1, 2 and 3 concern the following symbol, which describes a directional control valve.



1. Decide whether each of these statements is TRUE (T) or FALSE (F).

With the push-button not pressed:

- (i) Pressure is applied to port 4.
- (ii) Port 2 is vented.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

2. Decide whether each of these statements is TRUE (T) or FALSE (F).

When the push-button is pressed:

- (i) Pressure is applied to port 4.
- (ii) Port 2 is vented.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

3. Decide whether each of these statements is TRUE (T) or FALSE (F).

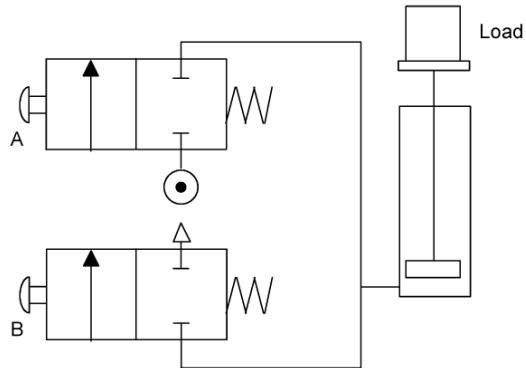
After pressing the push-button it is released, then:

- (i) Pressure is applied to port 2.
- (ii) Port 4 is vented.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

Questions 4 and 5 refer to the following figure, which shows a cylinder controlled by two pneumatic valves.



4. Decide whether each of these statements is TRUE (T) or FALSE (F).

- (i) When push-button A is pressed, the load is lifted.
- (ii) When push-button A is released, the load descends.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

5. Decide whether each of these statements is TRUE (T) or FALSE (F).

- (i) When push-button B is pressed, the load is lifted.
- (ii) When push-button B is released, the load remains either lifted or descended.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

6. Decide whether each of these statements is TRUE (T) or FALSE (F).

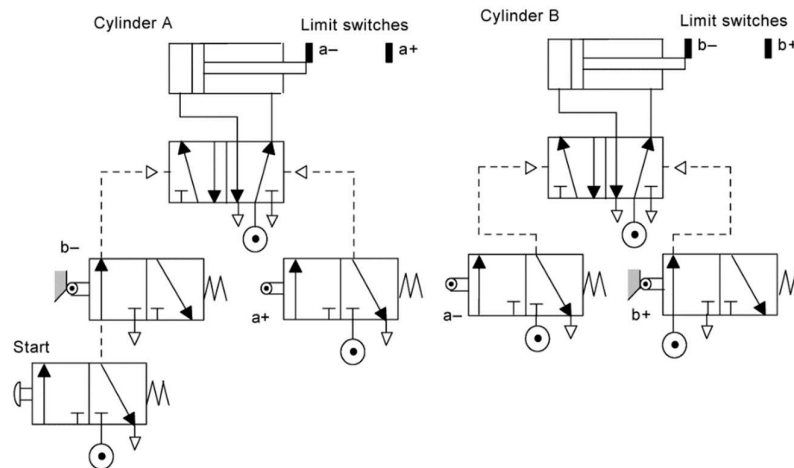
A process control valve with a quick-opening plug gives:

- (i) A change in flow rate that is proportional to the change in displacement of the valve stem.
- (ii) A large change in the flow rate for a small initial movement of the valve stem.

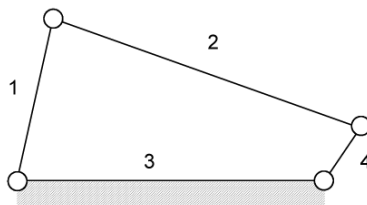
Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

7. For the pneumatic circuit given below, following the pressing of the start push-button the sequence is:



- A A+, B+, B-, A-
 - B A+, A-, B+, B-
 - C A+, B+, A-, B-
 - D A+, A-, B-, B+
8. Decide whether each of these statements is TRUE (T) or FALSE (F).
- Four links are connected as indicated in the following figure:



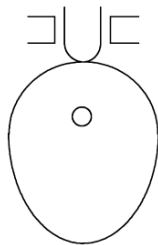
With the relative link lengths shown:

- (i) When link 4 rotates in a circular path, link 1 rotates in a circular path.
- (ii) If link 4 is made the same length as link 1 then when link 4 rotates, link 1 can only oscillate back-and-forth and not completely rotate.

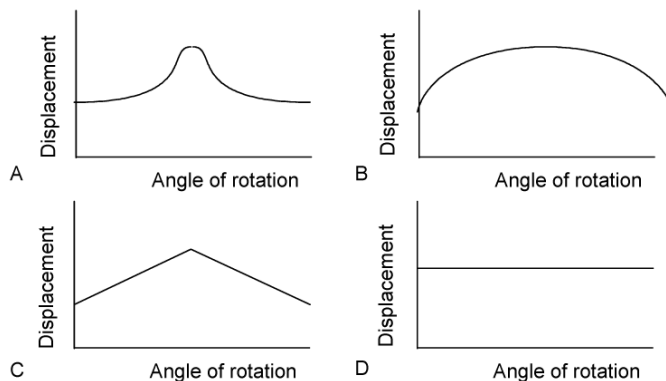
Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

9. The cam shown in the following figure rotates with a constant angular velocity.



The displacement of the follower is best described by:



10. A ball bearing is required to withstand radial loads and axial loads. The optimum bearing from the following is:

- A Deep groove.
- B Filling-slot.
- C Angular contact.
- D Self-aligning.

11. Decide whether each of these statements is TRUE (T) or FALSE (F).

For a thyristor:

- (i) When it is switched on and forward breakdown occurs, the thyristor resistance drops to a low value.
- (ii) The voltage at which a thyristor is switched on is determined by the current entering the gate.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

12. Decide whether each of these statements is TRUE (T) or FALSE (F).

For a series wound DC motor:

- (i) The direction of rotation of its shaft can be reversed by reversing the direction of the current supplied to the motor.
- (ii) The speed of rotation of the motor shaft can be controlled by varying the size of the current supplied to the motor.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

13. Decide whether each of these statements is TRUE (T) or FALSE (F).

For a shunt wound DC motor:

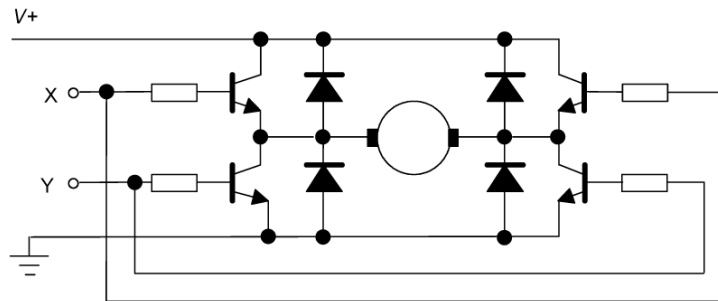
- (i) The direction of rotation of its shaft can be reversed by reversing the direction of the armature current.
- (ii) The speed of rotation of the motor shaft can be controlled by varying the size of the armature current.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

14. Decide whether each of these statements is TRUE (T) or FALSE (F).

The H-circuit shown below is used to control the current supplied to a DC motor.



- (i) For the motor to rotate, we must have both X and Y high.
- (ii) To reverse the motor, we must have both X and Y low.

Which option BEST describes the two statements?

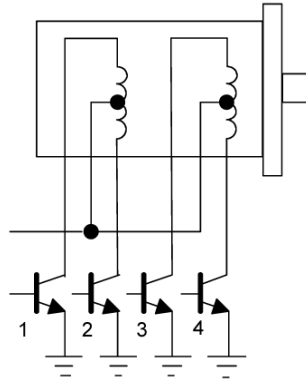
- A (i) T (ii) T
 - B (i) T (ii) F
 - C (i) F (ii) T
 - D (i) F (ii) F
15. Decide whether each of these statements is TRUE (T) or FALSE (F).
- A stepper motor is specified as having a step angle of 6° . This means that:
- (i) Each pulse input to the motor rotates the motor shaft by 6° .
 - (ii) An input of 300 pulses per second will cause it to rotate at 5 rev/s.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

16. Decide whether each of these statements is TRUE (T) or FALSE (F).

The figure below shows the unipolar connection for a stepper motor.



The motor will:

- (i) Rotate through one step when each transistor, 1, 2, 3 and 4, is switched on in turn, otherwise being off.
- (ii) Reverse its direction of rotation when the transistors are switched in the sequence 4, 3, 2 and 1, otherwise being off.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

TEST 3

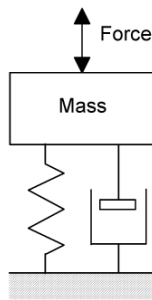
System models

For the following questions, you have four answer options A, B, C and D. Choose the correct answer from the answer options.

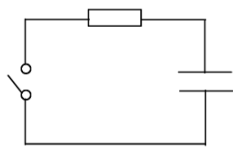
For each of questions 1 to 6, the differential equation that can be used to describe the variable in its variation with time is:

- A First-order with no forcing term.
- B First-order with a forcing term.
- C Second-order with no forcing term.
- D Second-order with a forcing term.

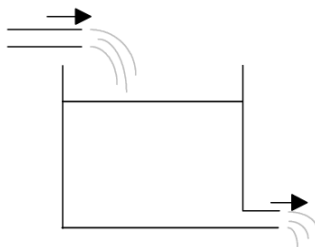
1. For the displacement of the mass in the basic mechanical system model shown below as a result of the applied force.



2. For the voltage across the initially charged capacitor when the switch is closed in the electrical system shown below.



3. For the temperature of a hot object cooling freely in air.
4. For the height of the water in the tank shown below.



5. For the voltage across the capacitor in a circuit containing a resistor, inductor and capacitor in series and supplied with an input of a step voltage.
6. For the temperature in an unlagged room when a heater is switched on.
7. Decide whether each of these statements is TRUE (T) or FALSE (F).
 - (i) If force F_1 produces an extension x_1 and force F_2 produces an extension x_2 , then a force which is $F_1 + F_2$ will produce an extension of $x_1 + x_2$.
 - (ii) If force F_1 produces an extension x_1 then a force of cF_1 will produce an extension of cx_1 .

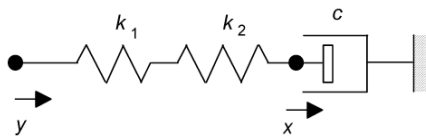
When we apply the principle of superposition, which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

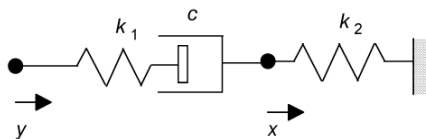
For questions 8 and 9, the differential equations describing how the displacement x varies with time when there is an input y that varies with time are:

- A $c \frac{dx}{dt} + k_1 k_2 x = 0$
- B $c(k_1 + k_2) \frac{dx}{dt} + k_1 k_2 x = ck_1 \frac{dy}{dt}$
- C $c \frac{dx}{dt} + (k_1 + k_2)x = 0$
- D $c \frac{dx}{dt} + (k_1 + k_2)x = (k_1 + k_2)y$

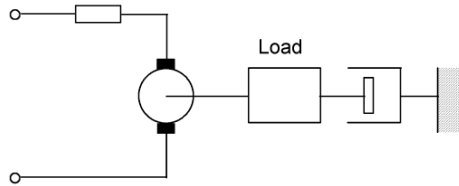
8. The springs-dashpot system shown below:



9. The springs-dashpot system shown below:



10. An armature-controlled DC motor has a resistance R_a and negligible inductance and is used to drive a rotational mechanical system that has a moment of inertia I and a damping coefficient c . The following figure illustrates the system.



With k_1 and k_2 being constants, the differential equation relating the angular speed ω of the load as a function of time with that of armature voltage v_a is:

- A $IR_a \frac{d\omega}{dt} + cR_a \omega = k_2 v_a$
- B $I \frac{d\omega}{dt} + c\omega = k_2 v_a$
- C $IR_a \frac{d\omega}{dt} + (cR_a + k_1 k_2) \omega = k_2 v_a$
- D $IR_a \frac{d\omega}{dt} = k_2 v_a$

11. Decide whether each of these statements is TRUE (T) or FALSE (F).

A system when described by the first-order differential equation

$$RC \frac{dv}{dt} + v = V$$

has a solution that gives:

- (i) A steady-state response of V .
- (ii) A transient response of $-V e^{-t/RC}$.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

12. Decide whether each of these statements is TRUE (T) or FALSE (F).

A second-order system has a response that:

- (i) Oscillates with time for ever if the damping factor is equal to 1.
- (ii) Slowly decays with time when the damping factor is greater than 1.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

13. For a system where the input y is related to the output x by the differential equation

$$a_1 \frac{dx}{dt} + a_0 x = b_0 y$$

the transfer function is:

- A $b_0/(a_1 + a_0)$
 - B $(a_0 + a_1)/b_0$
 - C $b_0/(a_1 s + a_0)$
 - D $(a_0 s + a_1)/b_0$
14. For a system with a transfer function $G(s)$ and subject to a unit step input, the output in the s -domain is:
- A $G(s)$
 - B $G(s)/s$
 - C $sG(s)$
 - D $1/s$
15. For a system with a transfer function $1/(s^2 + 6s + 9)$ when subject to a unit step input, the output as a function of time is:
- A Under-damped.
 - B Critically damped.
 - C Over-damped.
 - D An abrupt step.
16. A control system is a closed-loop with a forward-path transfer function of $1/(s + 1)$ and a negative feedback path transfer function of $4s$. The overall transfer function of the system is:
- A $1/(3s + 1)$
 - B $1/4s(s + 1)$
 - C $4s/(s + 1)$
 - D $1/(5s + 1)$
17. Decide whether each of these statements is TRUE (T) or FALSE (F).
- The frequency response of a system with a transfer function $1/(s + 1)$ has:
- (i) A magnitude of $1/\sqrt{1 + \omega^2}$.
 - (ii) A phase of $\tan^{-1}(-\omega)$.
- Which option BEST describes the two statements?
- A (i) T (ii) T
 - B (i) T (ii) F
 - C (i) F (ii) T
 - D (i) F (ii) F

18. Decide whether each of these statements is TRUE (T) or FALSE (F).

The Bode plot describes how, when a system is subject to a frequency input:

- (i) The magnitude of the output varies with time for a constant frequency.
- (ii) The phase of the output varies with time for a constant frequency.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

19. Decide whether each of these statements is TRUE (T) or FALSE (F).

With two-step control:

- (i) The controlled variable will tend to oscillate about the set value.
- (ii) The output of the controller is proportional to the error.

Which option BEST describes the two statements:

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

20. Decide whether each of these statements is TRUE (T) or FALSE (F).

With proportional control:

- (i) The controller output is proportional to the difference between the set value and the actual value of the variable.
- (ii) The controller gain is proportional to the difference between the set value and the actual value of the variable.

Which option BEST describes the two statements:

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

21. Decide whether each of these statements is TRUE (T) or FALSE (F).

With derivative control, the controller output is:

- (i) Proportional to the rate of change of the error.
- (ii) Zero when the error is constant.

Which option BEST describes the two statements:

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

22. Decide whether each of these statements is TRUE (T) or FALSE (F).

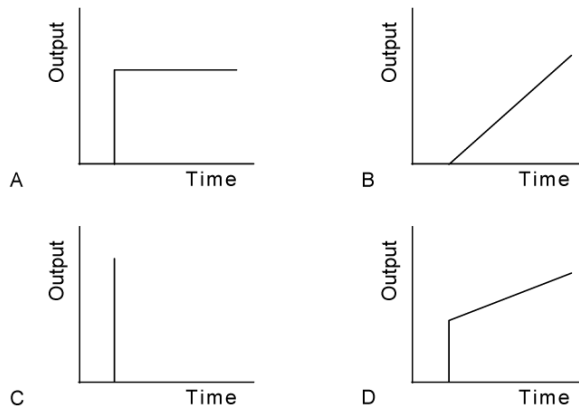
With integral control, the controller output:

- (i) Is zero when the error changes at a constant rate.
- (ii) Increases at a constant rate when the error is constant.

Which option BEST describes the two statements?

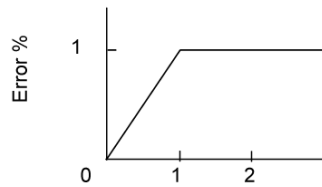
- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

Questions 23 to 26 involve controllers when there is a step error input. The following are controller outputs.



- 23. Which one will be the form of output for a proportional controller?
- 24. Which one will be the form of output for a derivative controller?
- 25. Which one will be the form of output for an integral controller?
- 26. Which one will be the form of output for a PI controller?

27. A PID controller has a proportional constant of 4, an integral time of 2 s and a derivative time of 0.5 s. The following figure shows the error input to the PID controller.



The controller output after 2 s will be:

- A 5%
 - B 7%
 - C 9%
 - D 16%
28. Decide whether each of these statements is TRUE (T) or FALSE (F).
- When the error signal increases from zero, when at the set point, to some value and then back to zero again:
- (i) With proportional control, the controller output mirrors the change and ends up back at zero.
 - (ii) With integral control, the controller output increases but does not end up back at zero when the error has ceased.

Which option among the following BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

TEST 4

Microprocessor systems

For the following questions, you have four answer options A, B, C and D. Choose the correct answer from the answer options.

1. The number of different words a microprocessor with a four-wire data bus can carry is:

A 4
B 8
C 16
D 32

2. The size of a memory unit needed with an address bus of 8 bits and 8-bit words is:

A 1K
B 2K
C 3K
D 4K

Questions 3 and 4 concern the following diagram, which shows part of the memory map of a Motorola M68HC11 microcontroller.

Address	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0	
1000	Bit 7							Bit 0	Port A
1001									Reserved
1002	STAF	STAI	CWOM	HNDS	OIN	PLS	EGA	INB	PIOC
1003	Bit 7							Bit 0	Port C
1004	Bit 7							Bit 0	Port B
1005	Bit 7							Bit 0	Port CL
1006									Reserved
1007	Bit 7							Bit 0	DDRC
1008								Bit 0	Port D
1009								Bit 0	DDRD

3. Data to be outputted from port B has to be written to address

A 1000
B 1003
C 1004
D 1007

4. Port C can be either an input or output; to control its direction, instructions should be sent to address
- A 1000
 - B 1002
 - C 1003
 - D 1007

Questions 5 to 9 involve the assembly language used for Motorola 6800-based systems.

5. Decide whether each of these statements is TRUE (T) or FALSE (F).

The mnemonic CLRA:

- (i) Enters all zeros in accumulator A.
- (ii) Is the inherent mode of addressing.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

6. Decide whether each of these statements is TRUE (T) or FALSE (F).

The mnemonic LDA \$00AF:

- (i) Adds to the contents of accumulator A the value 00AF.
- (ii) Is the absolute form of addressing.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

7. Decide whether each of these statements is TRUE (T) or FALSE (F).

The operation code EQU can be used to:

- (i) Define a value.
- (ii) Define the starting memory address.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

8. The following part of a program:

LDAA \$40

ADDA \$41

STAA \$42

WAI

- A Adds the numbers 40 and 41 and stores the results.
- B Loads address A with the data at addresses 41 and 42.
- C Takes the data at address 40 and replaces it by the data at address 41.
- D Adds the number at address 40 to the number at address 41 and stores it at address 42.

9. Decide whether each of these statements is TRUE (T) or FALSE (F).

The following part of a program:

LDAA \$40

ANDA # %00001111

STAA \$41

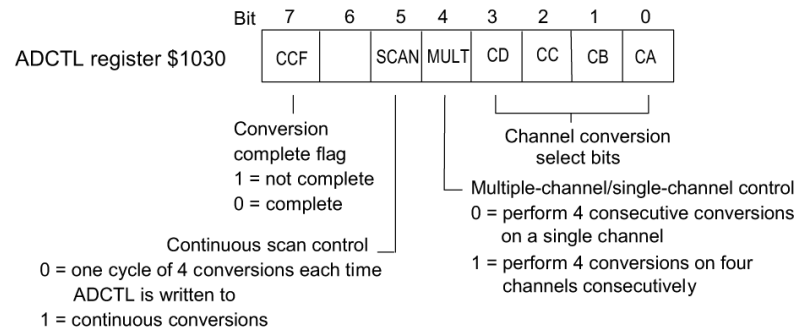
WAI

- (i) Gets data from address 40 and stores the result of the ANDA operation at address 41.
- (ii) Masks off the four most significant bits of the data.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

Questions 10 and 11 concern the Motorola 68HC11 microcontroller that has an internal analogue-to-digital converter powered up by writing to the OPTION register and then initiated by writing to the ADCTL register.



With MULT = 0

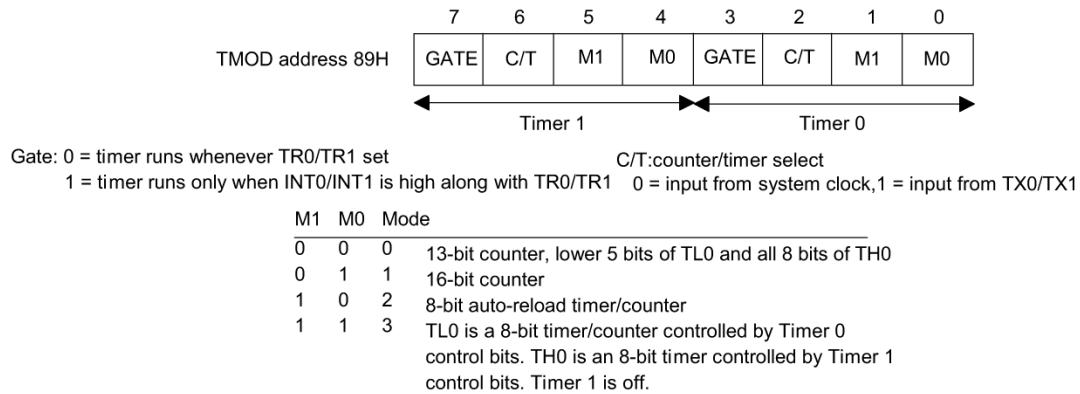
CD	CC	CB	CA	Channel converted
0	0	0	0	PE0
0	0	0	1	PE1
0	0	1	0	PE2
0	0	1	1	PE3
0	1	0	0	PE4
0	1	0	1	PE5
0	1	1	0	PE6
0	1	1	1	PE7

With MULT = 1

CD	CC	CB	CA	ADR1	ADR2	ADR3	ADR4
0	0	X	X	PE0	PE1	PE2	PE3
0	1	X	X	PE4	PE5	PE6	PE7

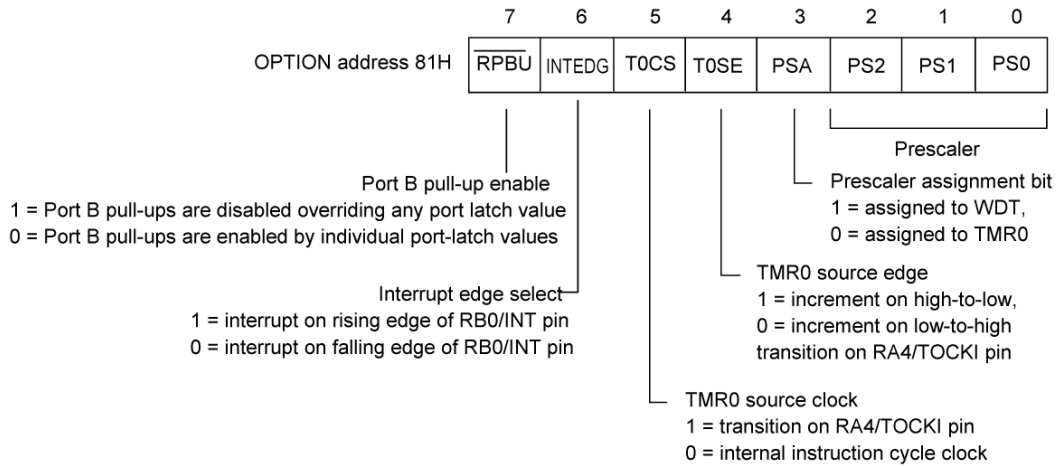
10. To give four successive A/D conversions on a single channel, register ADCTL has written to it:
- A 0000 0000
B 0000 0111
C 0001 0000
D 0001 0111
11. To give four conversions on four consecutive channels PE4, PE5, PE6 and PE7, register ADCTL has written to it:
- A 0000 0000
B 0000 0111
C 0001 0000
D 0001 0111

Questions 12 and 13 concern the Intel 8051 microcontroller and the timer control register TMOD that is used to set the operating modes for Timers 0 and 1.



12. To set the Intel 8051 microcontroller so that Timers 0 and 1 run whenever TR0 and TR1 are set, the following bits have to be set to 1:
 - Bits 0 and 4
 - Bits 1 and 5
 - Bits 2 and 6
 - Bits 3 and 7
13. To set the Intel 8051 microcontroller so that the Timers 0 and 1 operate as 8-bit auto-reload timers, the following bits have to be set to 1:
 - Bits 0 and 4
 - Bits 1 and 5
 - Bits 2 and 6
 - Bits 3 and 7
14. With PIC microcontrollers a bidirectional I/O port has port bits designated as read by writing:
 - 0 to the relevant port bit.
 - 1 to the relevant port bit.
 - 0 to the relevant TRIS bit.
 - 1 to the relevant TRIS bit.

15. The PIC microcontroller PIC 16C74 has three timers and a selection of which count source is to be used by the timers is made by setting the bits in the OPTION register.



To set the count source as the internal clock, the following bit must be set.

- A Bit 5 to 0
- B Bit 5 to 1
- C Bit 6 to 0
- D Bit 6 to 1

Questions 16 to 21 concern the use of C.

16. A line in a C program that begins with a # indicates that which follows is:

- A A decimal number.
- B A comment.
- C A pre-processor command.
- D An integer.

17. The line in a C program of:

`port C = port C ^ 1;`

causes the bits of port C to

- A Have 1s added to all bits.
- B Bit 1 to change from 1 to 0 or from 0 to 1.
- C Bit 1, whatever its value, to change to 1.
- D All the bits to invert.

18. Decide whether each of these statements is TRUE (T) or FALSE (F).

The lines in a C program of:

```
int a, b, c;
```

```
d = a * b * c;
```

indicates that:

- (i) a, b and c are to be integers.
- (ii) d is the product of a, b and c.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

19. The following C program displays:

```
#include <stdio.h>

int count;

main()
{
    for (count = 1; count <=100; count++)
        printf("\n%d", count);
}
```

- A The numbers 0 to 100 on the same line.
- B The number inputted between 0 and 100.
- C The numbers 0 to 100 on separate lines.
- D The number as a percentage.

Questions 20 and 21 concern the following C program.

```
#include <stdio.h>

int array[4];

main()
{
    int ctr = 0;
    int nbr = 0;
    printf("Enter 4 numbers\n");
    printf("Each number less than 10\n");
    while (ctr < 4)
```

```
{  
    nbr = 0;  
    while (nbr < 1 || nbr > 10)  
    {  
        printf("Enter number %d of 4: ", ctr + 1);  
        scanf("%d", &nbr);  
    }  
    array[ctr] = nbr;  
    ctr++;  
}  
for (ctr = 0; ctr < 4; ctr++)  
    printf("\n Value %d is %d", ctr + 1, array[ctr]);  
}
```

20. Decide whether each of these statements is TRUE (T) or FALSE (F).

The program:

- (i) Displays the request for four numbers to be entered.
- (ii) States that each number should be less than 10.

Which option BEST describes the two statements

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

21. Decide whether each of these statements is TRUE (T) or FALSE (F).

The program:

- (i) Asks that you enter number 1, then number 2, then number 3 and then number 4.
- (ii) Displays the sum of the four numbers.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

22. Decide whether each of these statements is TRUE (T) or FALSE (F).

With strobe-and-acknowledge handshaking:

- (i) Readiness to receive is indicated by a receiver.
- (ii) While data is being sent, the receiving device indicates not ready for further data.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

23. Decide whether each of these statements is TRUE (T) or FALSE (F).

With polling, when a peripheral device requires attention:

- (i) It activates an interrupt request line.
- (ii) The voltage level of the input line is changed.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

24. Decide whether each of these statements is TRUE (T) or FALSE (F).

With asynchronous serial interfacing:

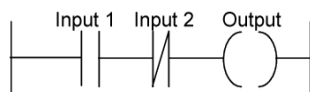
- (i) The receiver and the transmitter have a common clock signal.
- (ii) Each transmitted data word has to carry its own start and stop bits.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

25. Decide whether each of these statements is TRUE (T) or FALSE (F).

For the following rung of a ladder program, there is an output when:



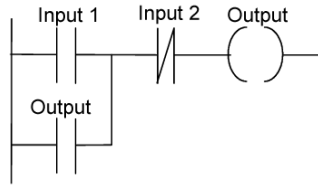
- (i) Just input 1 is activated.
- (ii) Just input 2 is activated.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

26. Decide whether each of these statements is TRUE (T) or FALSE (F).

For the following rung of a ladder program, there is an output when:



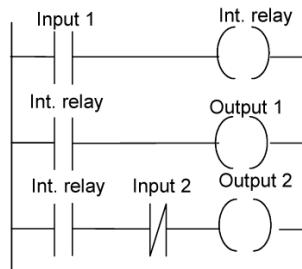
- (i) Input 1 is momentarily activated.
- (ii) Input 2 is not activated.

Which option BEST describes the two statements:

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

27. Decide whether each of these statements is TRUE (T) or FALSE (F).

For the following part of a ladder program involving an internal relay, there is:



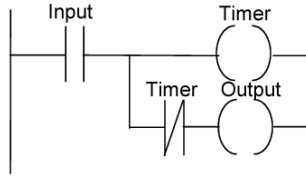
- (i) An output from output 1 when there is an input to input 1.
- (ii) An output from output 2 when there is an input to inputs 1 and 2.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

28. Decide whether each of these statements is TRUE (T) or FALSE (F).

For the part of the ladder program shown below and involving a delay-on timer set to a time of 5 s, the output:



- (i) Starts immediately after the input starts.
- (ii) Ceases 5 s after the start of the input.

Which option BEST describes the two statements:

- A (i) T (ii) T
 - B (i) T (ii) F
 - C (i) F (ii) T
 - D (i) F (ii) F
29. With two devices X and Y and the simplex mode of serial data transmission between the two, data can be:
- A Simultaneously transmitted from X to Y and Y to X.
 - B Only transmitted in one direction, X to Y or Y to X, at once.
 - C Sequentially transmitted, for example, from X to Y followed by Y to X.
 - D Only ever transmitted in one direction, for example, X to Y but not Y to X.
30. Decide whether each of these statements is TRUE (T) or FALSE (F).
- The IEEE-488 data transfer bus:
- (i) Is a parallel data bus.
 - (ii) Only allows one talker device to be connected to it.
- Which option BEST describes the two statements:
- A (i) T (ii) T
 - B (i) T (ii) F
 - C (i) F (ii) T
 - D (i) F (ii) F
31. Decide whether each of these statements is TRUE (T) or FALSE (F).
- An optoisolator is used to interface the input from a peripheral to a microprocessor to provide:
- (i) Electrical isolation.
 - (ii) Signal coupling.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

32. Decide whether each of these statements is TRUE (T) or FALSE (F).

Multiplexing of three 7-segment LED displays:

- (i) Activates the three displays simultaneously.
- (ii) Needs fewer I/O port lines than when not multiplexed.

Which option BEST describes the two statements?

- A (i) T (ii) T
- B (i) T (ii) F
- C (i) F (ii) T
- D (i) F (ii) F

33. A software solution to debounce a switch involves:

- A Detecting each individual switch closure and registering them.
- B Detecting only the biggest pulse from a switch closure.
- C Determining the average time of the pulses from a switch closure.
- D Instituting a delay after the first closure before registering the next.

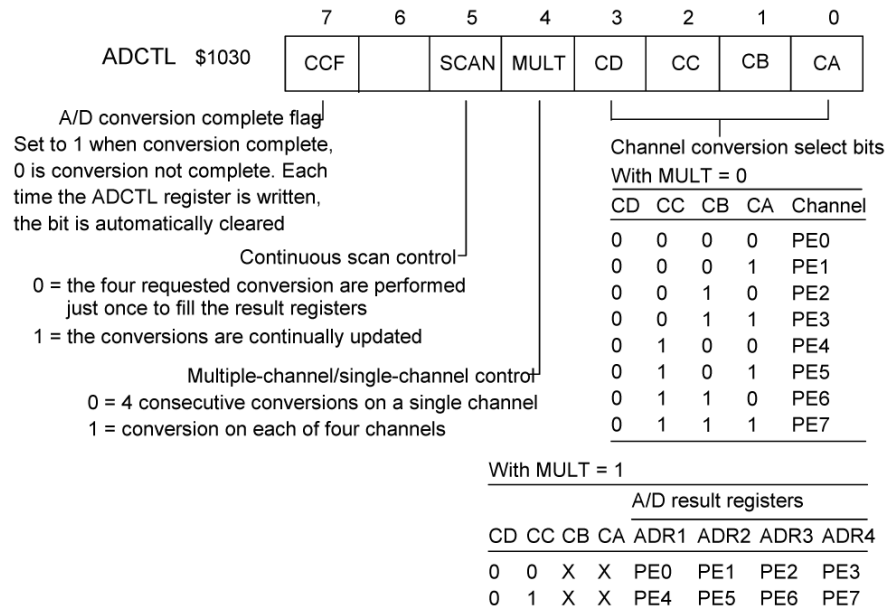
34. With two 7-segment LED displays, ripple blanking is used to:

- A Allow both displays to be simultaneously illuminated.
- B Allow a leading 0 to give no display.
- C Allow multiplexing of the two displays.
- D Allow a decimal point to be included in the display.

Questions 35 to 37 refer to the Motorola 68HC11 microcontroller and its integral eight-channel, 8-bit, multiplexed input ADC. The ADCTL register is used to control conversions.

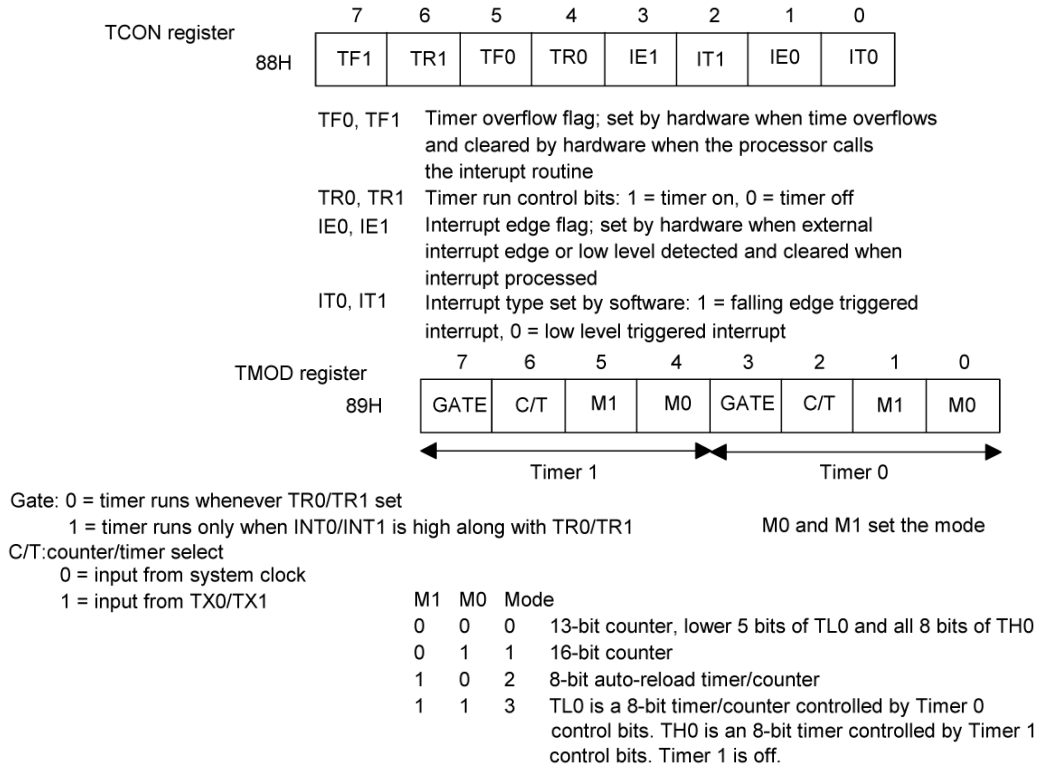
35. To operate as a single-channel system with four consecutive conversions and then the operation ceasing, it is necessary for ADCTL to have:

- A Bit 4 as 0, bit 5 as 0.
- B Bit 4 as 0, bit 5 as 1.
- C Bit 4 as 1, bit 5 as 0.
- D Bit 4 as 1, bit 5 as 1.



36. To operate as a multi-channel system with conversions on each of four channels and the conversions continually updated, it is necessary for ADCTL to have:
- A Bit 4 as 0, bit 5 as 0.
 - B Bit 4 as 0, bit 5 as 1.
 - C Bit 4 as 1, bit 5 as 0.
 - D Bit 4 as 1, bit 5 as 1.
37. To operate as a single-channel system for channel PE3, it is necessary for ADCTL to have:
- A Bit 0 as 0, bit 1 as 0, bit 2 as 0, bit 3 as 0, bit 4 as 0.
 - B Bit 0 as 1, bit 1 as 0, bit 2 as 0, bit 3 as 0, bit 4 as 0.
 - C Bit 0 as 1, bit 1 as 1, bit 2 as 0, bit 3 as 0, bit 4 as 0.
 - D Bit 0 as 0, bit 1 as 1, bit 2 as 1, bit 3 as 0, bit 4 as 0.

Questions 38 to 40 concern the Intel 8051 microcontroller. This has two internal timer/counters T0 and T1, which are initialised by setting bits in the TMOD register. Timing/counting is turned on by setting bits in the TCON register.



38. The program instruction MOV TMOD,#00000010B sets timer 0 as a:
- 13-bit counter.
 - 16-bit counter.
 - 8-bit autoloader counter.
 - TL0 as an 8-bit counter controlled by Timer 0, TH0 by Timer 1.
39. The program instruction to turn a timer on following the instruction MOV TMOD, #00000001B is:
- CLR TR0.
 - SETB TR0.
 - CLR TF0.
 - SETB TF0.
40. Following the instruction MOV TMOD, #00000001B, the timer overflow flag is set after a count of:
- $2^{8/12}$
 - 2^8
 - $2^{16/12}$
 - 2^{16}

41. Decide whether each of these statements is TRUE (T) or FALSE (F).
A stepper motor is specified as having a step angle of 6° . This means that:
(i) Each pulse input to the motor rotates the motor shaft by 6° .
(ii) An input of 300 pulses per second will cause it to rotate at 5 rev/s.
Which option BEST describes the two statements?
- A (i) T (ii) T
B (i) T (ii) F
C (i) F (ii) T
D (i) F (ii) F
42. An LED is to be connected to the latched output of a microprocessor system. If the output high from the latch is 5 V and the voltage drop across the LED is 1.7 V and the working current for the LED is 15 mA, the series resistor to be used with the LED is nominally:
- A 110 Ω .
B 220 Ω .
C 330 Ω .
D 450 Ω .

Answers to tests

1. Sensors and signal conditioning

1	D	2	C	3	A	4	C	5	A
6	B	7	C	8	B	9	D	10	A
11	D	12	B	13	B	14	D	15	A
16	A	17	A	18	A	19	C	20	B
21	B	22	A	23	D	24	A	25	B
26	B								

2. Actuation

1	A	2	D	3	D	4	B	5	C
6	C	7	B	8	D	9	A	10	C
11	A	12	C	13	A	14	D	15	A
16	D								

3. System models

1	D	2	A	3	A	4	B	5	D
6	B	7	A	8	D	9	B	10	C
11	A	12	C	13	C	14	B	15	B
16	D	17	A	18	D	19	B	20	B
21	A	22	C	23	A	24	C	25	B
26	D	27	B	28	A				

4. Microprocessor systems

1	C	2	B	3	C	4	D	5	A
6	C	7	B	8	D	9	A	10	C
11	B	12	D	13	B	14	D	15	A
16	C	17	B	18	A	19	C	20	A
21	B	22	A	23	C	24	C	25	B
26	A	27	B	28	A	29	D	30	B
31	A	32	C	33	D	34	B	35	A
36	D	37	C	38	C	39	B	40	D
41	A	42	B						

Supporting material: Electrical components and circuits

This supporting material is an extension of what was Appendix G in the previous edition and is designed to assist students who are not familiar with the basic elements of electricity.

Basic terms

The fundamental electrical quantity is **electrical charge** q and it has the unit of coulombs (C) and at the basic level with circuits arises from the presence of electrons, a negative charge, or an absence of electrons, a positive charge. Like charges repel each other, unlike charges attract. The force between charges is proportional to the sizes of the charges and inversely proportional to the square of the distance between them, this being known as **Coulomb's law**:

$$\text{Force} \propto \frac{(\text{size of charge 1})(\text{size of charge 2})}{(\text{distance between the charges})^2}$$

The rate of movement of electrical charge q past a point in a circuit is termed **current** (I), a rate of movement of 1 C per second being 1 ampere (A).

$$I = \frac{dq}{dt}$$

When there is a current through a circuit then charge is being moved through it and energy must be supplied to do this. The rate at which energy is required is called the **power**, the unit of power being the watt with one watt (W) being a rate of energy use of 1 joule per second. The term **voltage** or **potential difference** V is used for the energy required to move a unit charge between two points in an electrical circuit and has the unit of the volt (V).

$$\text{Power} = \frac{\text{energy}}{\text{time}} = \frac{\text{charge}}{\text{time}} \times \frac{\text{energy}}{\text{charge}} = IV$$

A potential difference of 1 V exists between two points in an electrical circuit carrying a current of 1 A when the power dissipated between these points is 1 W. A potential difference must always be measured relative to some reference point. It is thus customary to state voltages relative to the ground or body of the Earth as it can accept or supply charge without changing its electrical characteristic. The direction of the potential difference between two points in a circuit is indicated by an arrow between the points and which is parallel to the conductor, the arrow pointing towards the point which is taken to be more positive. Think of charge flowing down the potential hill of the circuit, with a cell pumping the charge back up to the top of the hill again, the arrow points uphill. The voltage supplied by a source of electrical energy, such as a battery or power supply, is called the **electromotive force** (emf). An ideal voltage source provides a voltage across its terminals that is independent of the resistance of the load connected across its terminals. However, real voltage sourced can only supply a limited amount of current and so a real voltage source is usually considered to be an ideal voltage source in series with a small resistance.

Figure 1 shows basic symbols used in electrical circuit diagrams. With the cell, the positive plate of the cell is the long line and the shorter fatter line is the negative plate. The convention adopted with electrical circuits is to indicate the direction of the current in a circuit conductor by an arrow on the conductor with current being taken as flowing out of the positive plate of a cell (the long line on the cell symbol), round the circuit and back into the negative plate (the short fat line on the symbol), the arrow for current indicating this direction. This is the convention that was originally adopted by those who first investigated electrical currents and who thought that current flow was caused by the motion of positive charge carriers rather than negative charge.

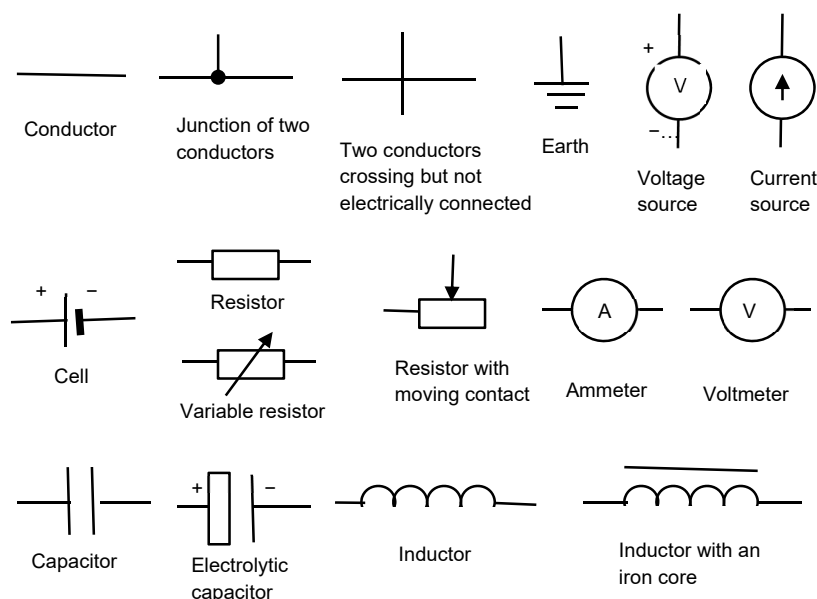


Figure 1 Basic electrical circuit symbols

Basic Electrical components

Basic electrical components are resistors, capacitors and inductors. The following is a brief discussion of them.

Resistors

For many materials the voltage V across an element is proportional to the current I through it, this being termed **Ohm's law**. The proportionality constant is termed the **resistance** R .

$$V = RI$$

Resistance has the unit ohms (Ω) when the voltage is in volts and the current amperes. The resistance of a uniform cross-section section of material, e.g. a wire, depends on its length L , cross-sectional area A , and the material concerned for which the term resistivity ρ is used.

$$R = \rho \frac{L}{A}$$

Resistivity has the unit $\Omega \text{ m}$. The term **electrical conductivity** σ is used for the reciprocal of the resistivity.

Resistors are supplied colour coded, the colour of bands on the resistor being used to specify numerical values. Four colour bands are used, the first indicating the first digit, the second the second digit, the third the number of zeros and the fourth the tolerance. The following table gives the colours and their significance.

Table Resistor colour code

Colour	Value	Colour	Value
Black	0	Gold	$\pm 5\%$
Brown	1	Silver	$\pm 10\%$
Red	2	No colour	$\pm 20\%$
Orange	3		
Yellow	4		
Green	5		
Blue	6		
Violet	7		
Grey	8		
White	9		

Capacitors

Capacitors are essentially just two parallel plates. When they are connected into a dc circuit charge gathers on one plate and the same amount of charge leaves the other plate. The potential difference V between the two plates is related to the magnitude of the charge Q on the plates by

$$V = \frac{Q}{C}$$

where C is the capacitance. With the voltage in volts, the charge in coulombs, then the capacitance is in farads (F). The unit of capacitance is the farad (F) when the charge is in coulombs and the potential difference in volts. A farad is a very large capacitance and more usually capacitances are in micro (10^{-6}) or pico (10^{-9}) farads.

Capacitors are available in a number of forms. Paper capacitors consist a layer of waxed paper sandwiched between two layers of metal foil, the whole being wound into a roll. Plastic capacitors have a similar construction with a layer of plastic between two layers of metal foil. Ceramic capacitors consist of essentially a ceramic plate silvered on opposite faces. Electrolytic capacitors consist of two sheets of aluminium foil separated by a thick absorbent material impregnated with an electrolyte, the whole arrangement being rolled into a coil and put in an aluminium can. When a voltage is applied to the capacitor a thin layer of aluminium oxide is formed on the positive plate and this forms the dielectric. Such a capacitor must always be used with a d.c. supply and always connected with the correct polarity.

Inductors

A current passing through a coil produces a magnetic field. When the current through the coil changes, the magnetic field changes and an emf e is induced in the coil which is proportional to the rate of change of the current (Faraday's law). The constant of proportionality L is called the inductance and has a unit of the Henry (H) when the emf is in volts, the current in amps and the time in seconds.

$$e = L \frac{di}{dt}$$

Direct current resistor circuits

The fundamental laws used in circuit analysis are Kirchhoff's laws:

- 1 **Kirchhoff's current law** states that at any junction in an electrical circuit, the current entering it equals the current leaving it.
- 2 **Kirchhoff's voltage law** states that around any closed path in a circuit, the sum of the voltage drops across all the components is equal to the sum of the applied voltage rises.

For resistors in series (Figure 2(a)) there is the same current through each resistor. The total voltage drop across them is:

$$V = V_1 + V_2 = IR_1 + IR_2 = I(R_1 + R_2)$$

Thus, we could replace the two series resistors with a single resistor R where $R = R_1 + R_2$.

For resistors in parallel (Figure 2(b)) there is the same voltage across each resistor. The total current entering them is:

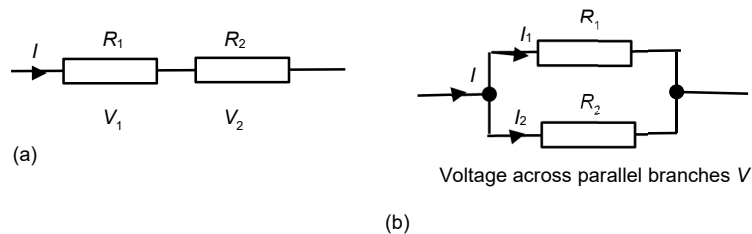


Figure 2 (a) Resistors in series, (b) resistors in parallel

$$I = I_1 + I_2 = \frac{V}{R_1} + \frac{V}{R_2}$$

Since $I = V/R$, where R is the total resistance of the arrangement

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

While circuits containing combinations of series- and parallel-connected resistors can often be reduced to a simple circuit by systematically determining the equivalent resistance of series or parallel connected resistors and reducing the analysis problem to a very simple circuit the techniques given in the next section are likely to be needed for more complex circuits.

An arrangement used in many electronic circuits is the **voltage divider**. The reference input voltage can be applied across two series resistors and the output voltage taken from across one of them (Figure 3(a)). With no load on the output circuit there is no current taken from the circuit and so the current through the two series resistors is $I = V/(R_1 + R_2)$. The voltage across R_2 is thus $IR_2 = R_2/(R_1 + R_2)$. Figure 3(b) shows the same type of arrangement with a potentiometer, the sliding contact changing the relative values of R_1 and R_2 .

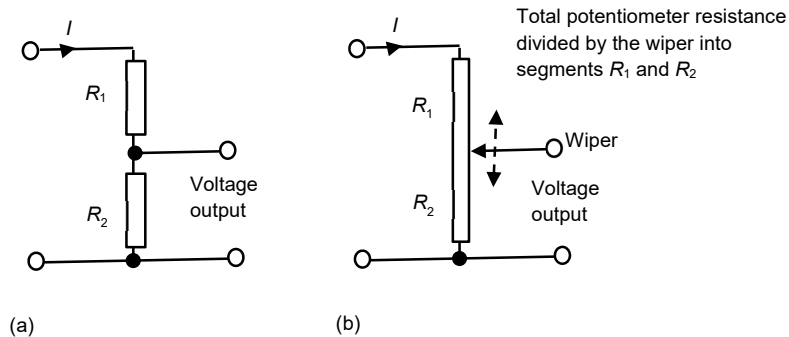


Figure 3 Voltage divider circuit

Node analysis

A **node** is a point in a circuit where two or more devices are connected together, i.e. it is a junction at which we have current entering and current leaving. A **principal node** is a point where three or more elements are connected together. Thus, in Figure 4, just b and d are principal nodes. One of the principal nodes is chosen to be a reference node so that the potential differences at the other nodes are then considered with reference to it. For the following analysis with Figure 4, d has been taken as the reference node. Kirchhoff's current law is then applied to each non-reference node. The procedure is thus:

- 1 Draw a labelled circuit diagram and mark the principal nodes.
- 2 Select one of the principal nodes as a reference node.
- 3 Apply Kirchhoff's current law to each of the non-reference nodes, using Ohm's law to express the currents through resistors in terms of node voltages.
- 4 Solve the resulting simultaneous equations. If there are n principal nodes there will be $(n - 1)$ equations.
- 5 Use the derived values of the node voltages to determine the currents in each branch of the circuit.

As an illustration, consider Figure 3. The nodes are a, b, c and d with b and d being principal nodes. Take node d as the reference node.

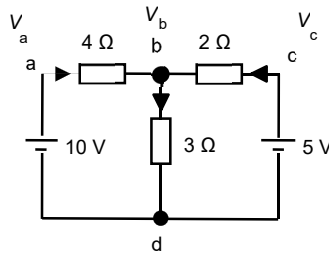


Figure 4 Circuit for node analysis

If V_a , V_b and V_c are the node voltages relative to node d then the potential difference across the $4\ \Omega$ resistor is $(V_a - V_b)$, across the $3\ \Omega$ resistor is V_b and across the $2\ \Omega$ resistor is $(V_c - V_b)$. Thus, the current through the $4\ \Omega$ is $(V_a - V_b)/4$, through the $3\ \Omega$ resistor is $V_b/3$ and through the $2\ \Omega$ resistor is $(V_c - V_b)/2$. Thus, applying Kirchhoff's current law to node b gives:

$$\frac{V_a - V_b}{4} + \frac{V_c - V_b}{2} = \frac{V_b}{3}$$

But $V_a = 10\text{ V}$ and $V_c = 5\text{ V}$ and so:

$$\frac{10 - V_b}{4} + \frac{5 - V_b}{2} = \frac{V_b}{3}$$

Thus $V_b = 4.62\text{ V}$. The potential difference across the $4\ \Omega$ resistor is thus $10 - 4.62 = 5.38\text{ V}$ and so the current through it is $5.38/4 = 1.35\text{ A}$. The potential difference across the $3\ \Omega$ resistor is 4.62 V and so the current through it is $4.62/3 = 1.54\text{ A}$. The potential difference across the $2\ \Omega$ resistor is $5 - 4.62 = 0.38\text{ V}$ and so the current through it is $0.38/2 = 0.19\text{ A}$.

Mesh analysis

The term **loop** is used for a sequence of circuit elements that form a closed path. A **mesh** is a circuit loop which does not contain any other loops within it. Mesh analysis involves defining a current as circulating round each mesh. The same direction must be chosen for each mesh current and the usual convention is to make all the mesh currents circulate in a clockwise direction. Having specified mesh currents, Kirchhoff's voltage law is then applied to each mesh. The procedure is thus:

- 1 Label each of the meshes with clockwise mesh currents.
- 2 Apply Kirchhoff's voltage law to each of the meshes, the potential differences across each resistor being given by Ohm's law, i.e. $V = IR$, in terms of the current through it and in the opposite direction to the current. The current through a resistor which borders just one mesh is the mesh current; the current through a resistor bordering two meshes is the algebraic sum of the mesh currents through the two meshes.

- 3 Solve the resulting simultaneous equations to obtain the mesh currents. If there are n meshes there will be n equations.
- 4 Use the results for the mesh currents to determine the currents in each branch of the circuit.

As an illustrating, for the circuit shown in Figure 5 there are three loops ABCF, CDEF and ABCDEF but only the first two are meshes. We can define currents I_1 and I_2 as circulating in a clockwise direction in these meshes.

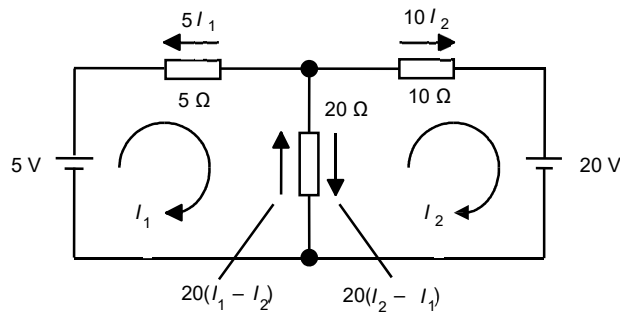


Figure 5 Circuit illustrating mesh analysis

For mesh 1, applying Kirchhoff's voltage law gives $5 - 5I_1 - 20(I_1 - I_2) = 0$. This can be rewritten as:

$$5 = 25I_1 - 20I_2$$

For mesh 2, applying Kirchhoff's voltage law gives $-10I_2 - 20 - 20(I_2 - I_1) = 0$. This can be rewritten as:

$$20 = 20I_1 - 30I_2$$

We now have a pair of simultaneous equations and so $I_2 = -1.14$ A and $I_1 = -0.71$ A. The minus signs indicate that the currents are in the opposite directions to those indicated in the figure. The current through the $20\ \Omega$ resistor is thus, in the direction of I_1 and $-0.71 + 1.14 = 0.43$ A.

Thévenin's theorem

The equivalent circuit for any two-terminal network containing a voltage or current source is given by **Thévenin's theorem**:

Any two-terminal network (Figure 6(a)) containing voltage or current sources can be replaced by an equivalent circuit consisting of a voltage equal to the open-circuit voltage of the original circuit in series with the resistance measured between the terminals when no load is connected between them and all independent sources in the network are set equal to zero (Figure 6(b)).

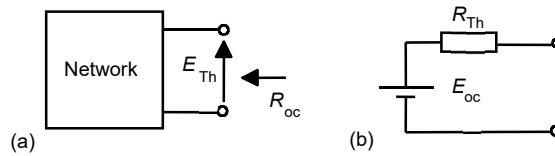


Figure 6 (a) The network, (b) its equivalent

If we have a linear circuit, to use Thévenin's theorem we have to divide it into two circuits, A and B, connected at a pair of terminals. We can then use Thévenin's theorem to replace, say, circuit A by its equivalent circuit. The open-circuit Thévenin voltage for circuit A is that given when circuit B is disconnected and the Thévenin resistance for A is the resistance looking into the terminals of A with all its independent sources set equal to zero. Figure 7 illustrates this sequence of steps.

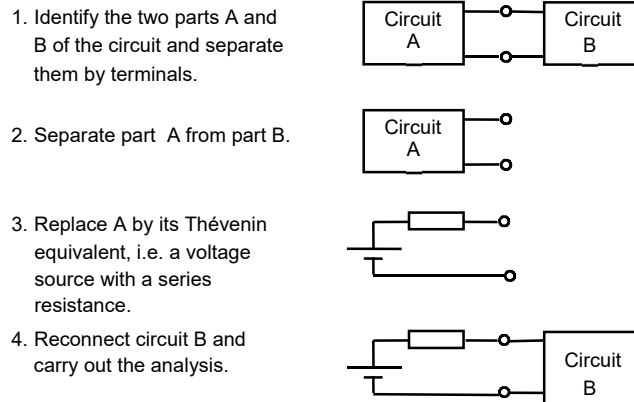


Figure 7 Step-by-step approach for circuit analysis

As an illustration consider the use of Thévenin's theorem to determine the current through the $10\ \Omega$ resistor in the circuit given in Figure 8.

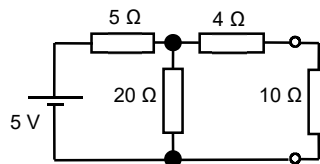


Figure 8 Example circuit illustrating the use of Thévenin's theorem

Since we are interested in the current through the $10\ \Omega$ resistor we identify it as network B and the rest of the circuit as network A, connecting them by terminals (Figure 9(a)). We then separate A from B (Figure 9(b)) and determine the Thévenin equivalent for it. The open-circuit voltage is that across the $20\ \Omega$ resistor, i.e. the fraction of the total voltage drop across the $20\ \Omega$.

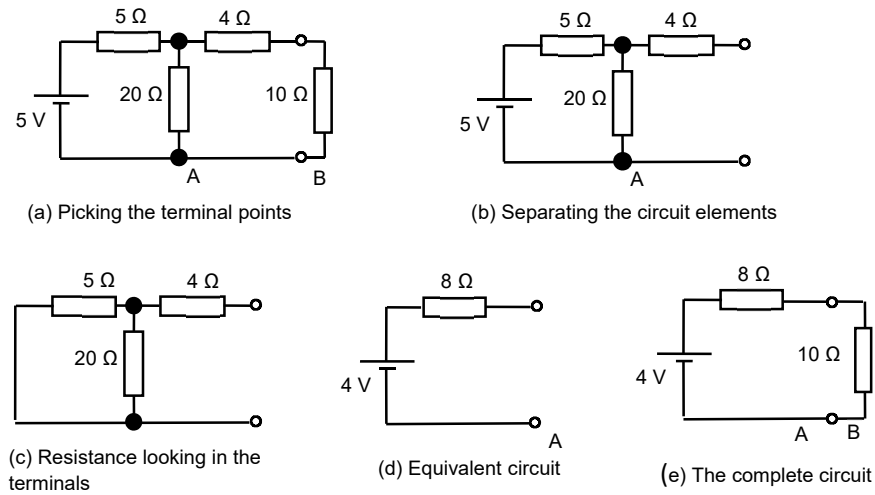


Figure 9 The Thévenin analysis

$$E_{Th} = 5 \frac{20}{20 + 5} = 4 \text{ V}$$

The resistance looking into the terminals when voltage source is equal to zero is that of 4Ω in series with a parallel arrangement of 5Ω and 20Ω (Figure 9(c)).

$$R_{Th} = 4 + \frac{20 \times 5}{20 + 5} = 8 \Omega$$

Thus, the equivalent Thévenin circuit is as shown in Figure 9(d) and when network B is connected to it we have the circuit shown in Figure 9(e). Hence the current through the 10Ω resistor is $I_{10} = 4 / (8 + 10) = 0.22 \text{ A}$.

Norton's theorem

In a similar way to Thévenin's theorem, we can have an equivalent circuit for any two-terminal network containing voltage or current sources in terms of an equivalent network of a current source shunted by a resistance. This is known as **Norton's theorem**:

Any two-terminal network containing voltage or current sources can be replaced by an equivalent network consisting of a current source, equal to the current between the terminals when they are short-circuited, in parallel with the resistance measured between the terminals when there is no load between them and all independent sources in the network are set equal to zero.

If we have a linear circuit we have to divide it into two circuits, A and B, connected at a pair of terminals (Figure 10). We can then use Norton's theorem to replace, say, circuit A by its equivalent circuit. The short-circuit Norton current for circuit A is that given when circuit B is disconnected and the Norton resistance for A is the resistance looking into the terminals of A with all its independent sources set equal to zero.

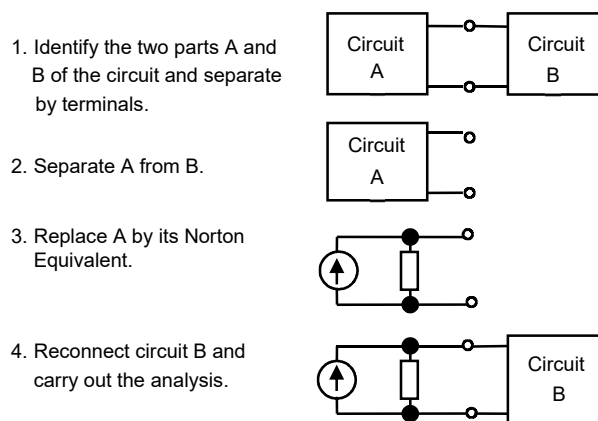


Figure 10 Step-by-step approach for circuit analysis using Northon's theorem

As an illustration of the use of Norton's theorem, consider the determination of the current I through the $20\ \Omega$ resistor in Figure 11.

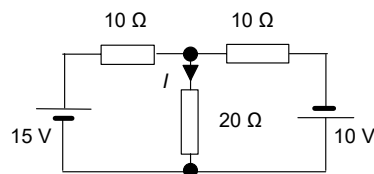


Figure 11 Circuit for analysis using Norton's theorem

We can redraw the circuit in the form shown in Figure 12(a) as two connected networks A and B with network B is selected to be the $20\ \Omega$ resistor through which we require the current. We then determine the Norton equivalent circuit for network A (Figure 12(b)). Short-circuiting the terminals of network A gives the circuit shown in Figure 12(c). The short circuit current will be the sum, taking into account directions, of the currents from the two branches of the circuits containing the voltage sources, i.e. $I_{sc} = I_1 - I_2$. The current $I_1 = 15/10 = 1.5\text{ A}$, since the other branch of the network is short-circuited, and $I_2 = 10/10 = 1.0\text{ A}$. Thus $I_{sc} = 0.5\text{ A}$. The Norton resistance is given by that across the terminals when all the sources are set to zero (Figure 12(d)). It is thus:

$$R_N = \frac{10 \times 10}{10 + 10} = 5\ \Omega$$

Thus, the Norton equivalent circuit is that shown in Figure 12(e). Hence when we put this with network B (Figure 12(f)) we can obtain the current I . The p.d. across the resistors is $0.5 \times R_{total}$ and so the current I is this p.d. divided by 20. Hence:

$$I = 0.5 \times \frac{5}{5 + 20} = 0.1\text{ A}$$

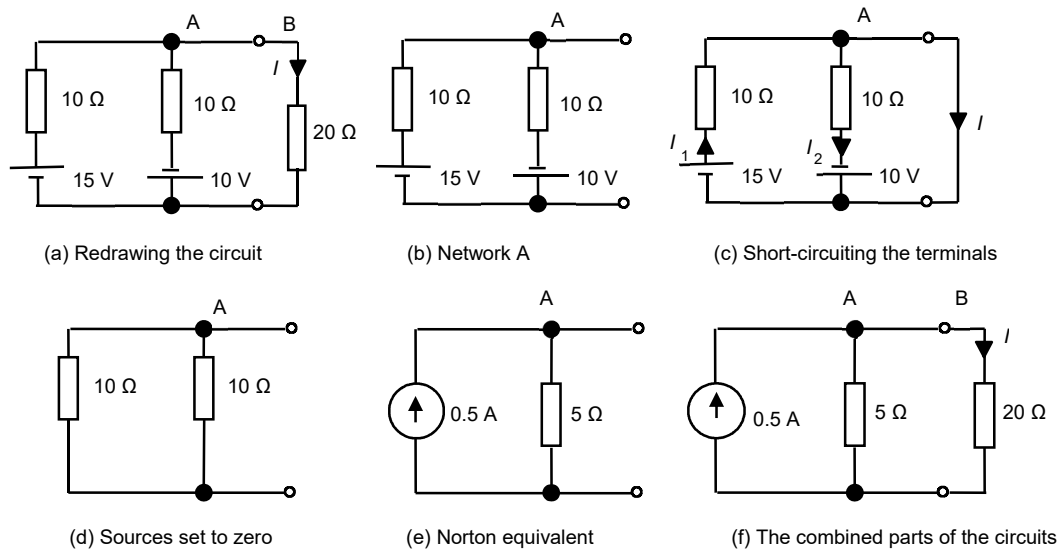


Figure 12 The Norton analysis

Resistor, capacitor and inductor circuits

When capacitors are connected in series (Figure 13(a)), the total voltage V across the series arrangement will be the sum of the voltages across each capacitor, i.e. $V = V_1 + V_2 + V_3$. As $V = Q/C$, then:

$$\frac{Q}{C} = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3}$$

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

For capacitors connected in parallel (Figure 13(b)), the total voltage V across each of the capacitors in the parallel arrangement is the same. The charges on each capacitor will depend on their capacitance. The total charge shared between the capacitors is thus $Q = Q_1 + Q_2 + Q_3$ and so:

$$CV = C_1V + C_2V + C_3V$$

$$C = C_1 + C_2 + C_3$$

For a discussion of d.c. circuits which include resistors, capacitors and inductors see Chapter 17.3.1 and Chapters 19.3 and 19.4.

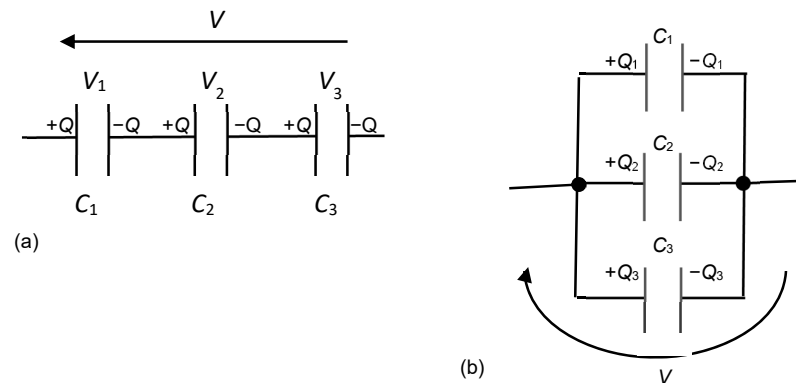


Figure 13 (a) Series capacitors, (b) parallel capacitors

Alternating current circuits

We can generate a sinusoidal waveform by rotating a radius line OA at a constant angular velocity ω (Figure 13(a)), the vertical projection of the line AB varying with time in a sinusoidal manner. The angle θ of the AB at a time t is ωt . The frequency f of rotation is $1/T$, where T is the time taken for one complete rotation, and so $\omega = 2\pi f$. In Figure 13(a) the rotating line OA was shown as starting from the horizontal position at time $t = 0$.

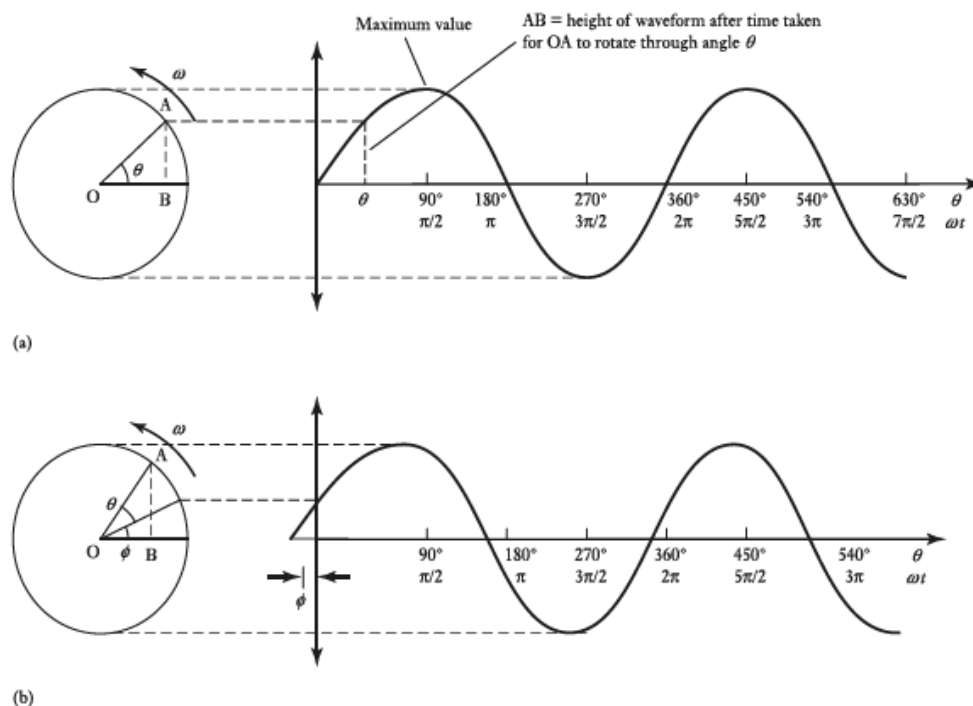


Figure 13 Generating sinusoidal waveforms (a) zero value at time $t = 0$, (b) an initial value at $t = 0$

Figure 13(b) shows the line OA at $t = 0$ is already at some angle ϕ . As the line OA rotates with an angular velocity ω then in a time t the angle swept out is ωt and thus at time t the angle with respect to the horizontal is $\omega t + \phi$. Sinusoidal alternating currents and voltages can be described by such rotating lines and hence by the equations $i = I_m \sin \omega t$ and $v = V_m \sin \omega t$ for currents and voltages with zero values at time $t = 0$ and for those starting at some initial angle ϕ by $i = I_m \sin (\omega t + \phi)$ and $v = V_m \sin (\omega t + \phi)$. Lowercase symbols are used for the current and voltage terms that change with time, uppercase being reserved for the non-varying terms.

With alternating current circuits there is a need to consider the relationship between an alternating current through a component and the alternating voltage across it. If we take the alternating current as the reference for a series circuit and consider it to be represented by $i = I_m \sin \omega t$, then the voltage may be represented by $v = V_m \sin (\omega t + \phi)$. There is said to be a **phase difference** of ϕ between the current and the voltage. If ϕ has a positive value then the voltage is said to be **leading** the current (as in Figure 13 if (a) represents the current and (b) the voltage), if a negative value then **lagging** the current.

We can just describe a sinusoidal alternating current by just specifying the rotating line in terms of its length and its initial angle relative to a horizontal reference line. The term **phasor**, being an abbreviation of the term phase vector, is used for such lines. The length of the phasor can represent the maximum value of the sinusoidal waveform or the root-mean-square value, since the maximum value is proportional to the root-mean-square value. Because currents and voltages in the same circuit will have the same frequency and thus the phasors used to represent them will rotate with the same angular velocity and maintain the same phase angles between them at all times we do not need to bother about drawing the effects of their rotation but can just draw phasor diagrams giving the relative angular positions of the phasors and ignore their rotations.

The following summarise the main points about phasors:

- 1 A phasor has a length that is directly proportional to the maximum value of the sinusoidally alternating quantity or, because the maximum value is proportional to the root-mean-square value, a length proportional to the r.m.s. value.
- 2 Phasors are taken to rotate anticlockwise and have an arrow-head at the end which rotates.
- 3 The angle between two phasors shows the phase angle between their waveforms. The phasor which is at a larger anticlockwise angle is said to be leading, the one at the lesser anticlockwise angle lagging.
- 4 The horizontal line is taken as the reference axis and one of the phasors given that direction, the others have their phase angles given relative to this reference axis.

Resistance, inductance and capacitance in a.c. circuits

Consider a sinusoidal current $i = I_m \sin \omega t$ passing through a **pure resistance**. A pure resistance is one that has only resistance and no inductance or capacitance. Since we can assume Ohm's law to apply, then the voltage v across the resistance must be $v = Ri$ and so $v = RI_m \sin \omega t$. The current and the voltage are thus in phase. The maximum voltage will be when $\sin \omega t = 1$ and so $V_m = RI_m$ and we can write $v = V_m \sin \omega t$.

Consider a sinusoidal current $i = I_m \sin \omega t$ passing through a **pure inductance**. A pure inductance is one which has only inductance and no resistance or capacitance. With an inductance a changing

current produces a back e.m.f. of $L \, di/dt$, where L is the inductance. The applied e.m.f. must overcome this back e.m.f. for a current to flow. Thus, the voltage v across the inductance is $L \, di/dt$ and so

$$v = L \frac{di}{dt} = L \frac{d}{dt}(I_m \sin \omega t) = \omega L I_m \cos \omega t$$

Since $\cos \omega t = \sin(\omega t + 90^\circ)$, the current and the voltage are out of phase with the voltage leading the current by 90° . The maximum voltage is when $\cos \omega t = 1$ and so we have $V_m = \omega L I_m$. V_m/I_m is called the **inductive reactance** X_L . Thus $X_L = V_m/I_m = \omega L$. Since $\omega = 2\pi f$ then $X_L = 2\pi f L$ and so the reactance is proportional to the frequency f . The higher the frequency the greater the opposition to the current.

Consider a circuit having just **pure capacitance** with a sinusoidal voltage $v = V_m \sin \omega t$ being applied across it. A pure capacitance is one which has only capacitance and no resistance or inductance. The charge q on the plates of a capacitor is related to the voltage v by $q = Cv$. Thus, since current is the rate of movement of charge dq/dt , we have $i = \text{rate of change of } q = \text{rate of change of } (Cv) = C \times (\text{rate of change of } v)$, i.e. $i = C \, dv/dt$. Thus

$$i = \frac{dq}{dt} = \frac{d}{dt}(Cv) = C \frac{d}{dt}(V_m \sin \omega t) = \omega C V_m \cos \omega t$$

Since $\cos \omega t = \sin(\omega t + 90^\circ)$, the current and the voltage are out of phase, the current leading the voltage by 90° . The maximum current occurs when $\cos \omega t = 1$ and so $I_m = \omega C V_m$. V_m/I_m is called the **capacitive reactance** X_C . Thus $X_C = V_m/I_m = 1/\omega C$. The reactance has the unit of ohms and is a measure of the opposition to the current. The bigger the reactance the greater the voltage has to be to drive the current through it. Since $\omega = 2\pi f$, the reactance is inversely proportional to the frequency f and so the higher the frequency the smaller the opposition to the current. With d.c., i.e. zero frequency, the reactance is infinite and so no current flows.

In summary, Figure 14 shows the voltage and current phasors for (a) pure resistance, (b) pure inductance, (c) pure capacitance.

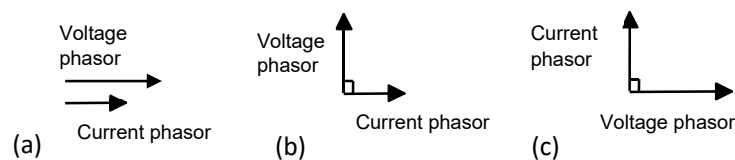


Figure 14 Phasors with (a) pure resistance, (b) pure inductance, (c) pure capacitance

Series a.c. circuits

For a series circuit, the total voltage is the sum of the p.d.s across the series components, though the p.d.s may differ in phase. This means that if we consider the phasors, they will rotate with the same angular velocity but may have different lengths and start with a phase angle between them. We can obtain the sum of two series voltages by using the **parallelogram law** of vectors to add the two phasors:

If two phasors are represented in size and direction by adjacent sides of a parallelogram, then the diagonal of that parallelogram is the sum of the two (Figure 15).

If the phase angle between the two phasors of sizes V_1 and V_2 is 90° , then the resultant can be calculated by the use of the Pythagoras theorem as having a size V given by $V^2 = V_1^2 + V_2^2$ and a phase angle ϕ relative to the phasor for V_1 given by $\tan \phi = V_2/V_1$.

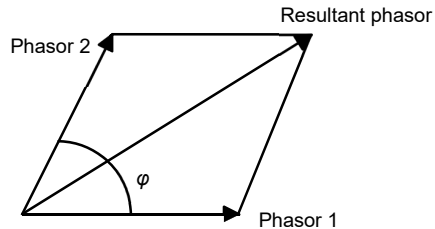


Figure 15 Adding phasors 1 and 2 which have a phase angle ϕ between them

As an illustration of the use of the above, consider an alternating current circuit having resistance in series with inductance (Figure 16(a)). For such a circuit, the voltage for the resistance is in phase with the current and the voltage for the inductor leads the current by 90° . Thus, the phasor for the sum of the voltage drops across the two series components is given by Figure 16(b) as a voltage phasor with a phase angle ϕ . We can use the Pythagoras theorem to give the magnitude V of the voltage, i.e. $V^2 = V_R^2 + V_L^2$, and trigonometry to give the phase angle ϕ , i.e. the angle by which the voltage leads the current as $\tan \phi = V_L/V_R$ or $\cos \phi = V_R/V$.

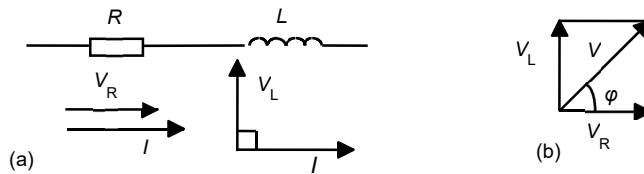


Figure 16 *RL* series circuit

Since $V_R = IR$ and $V_L = IX_L$ then $V^2 = (IR)^2 + (IX_L)^2 = I^2(R^2 + X_L^2)$. The term **impedance** Z is used for the opposition of a circuit to the flow of current, being defined as $Z = V/I$ with the unit of ohms. Thus, for the resistance and inductance in series, the circuit impedance is given by

$$Z = \sqrt{R^2 + X_L^2} = \sqrt{R^2 + (\omega L)^2}$$